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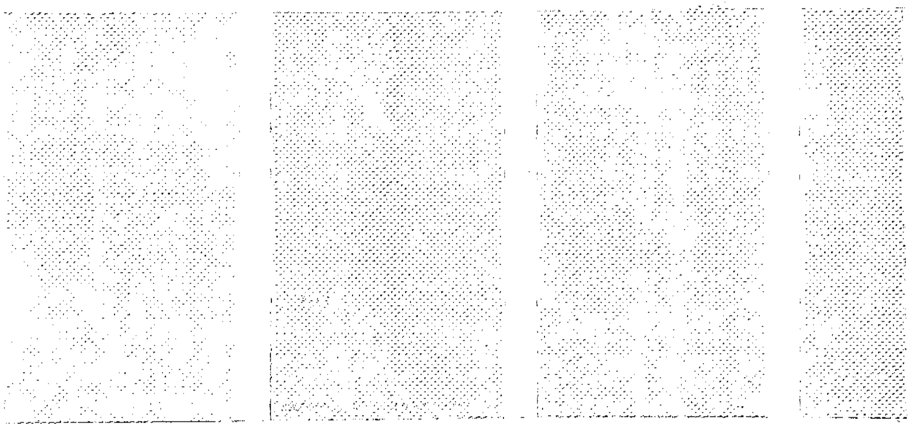

HYDROLOGY RESEARCH PROGRAM

New Mexico Institute of Mining and Technology

Socorro, New Mexico 87801

A BASELINE STUDY OF OXYGEN 18 AND DEUTERIUM IN THE ROSWELL, N.M., GROUNDWATER BASIN*

by

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*Based on research performed by R.N. Hoy in partial fulfillment of the requirements for the degree of M.S. in Geoscience with specialization in Hydrology.

ABSTRACT

The isotopic ratios of deuterium and oxygen 18 were measured in precipitation, surface, and groundwater samples from the Roswell Artesian groundwater basin in south-central New Mexico. The purpose was to determine recharge and circulation patterns. The results would supplement earlier studies based on tritium ratios and hydrogeologic surveys. The study area comprises about 8000 square miles with elevations ranging from 3,400 ft a.m.s.l. to almost 12,000 ft. Except for minor deviations due to evaporation, the samples measured for this study conform to the meteoric water line. No exchange reactions with aquifer rock seem to have taken place. While the δD vs. $\delta^{18}O$ values of precipitation are spread over the whole usual range of the meteoric water line, well and spring samples (reflecting groundwater) lie within a relatively narrow range ($\delta D = - 30^{o}/oo$ to $-80^{o}/oo$ and $\delta^{18}O = - 60^{o}/oo$ to $-10^{o}/oo$, all with respect to Standard Mean Ocean Water). Exceptions outside of this range are minor and can be attributed to evaporation effects. Well waters of the Principal Artesian Aquifer average $\delta D = - 51^{o}/oo$, $\delta^{18}O = - 8^{o}/oo$. The narrow range of δD and $\delta^{18}O$ indicates mixing effects which are ascribed to one or more of the following factors: long groundwater flow paths; large temperature fluctuations affecting all parts of the Basin and which overwhelm the influence of elevation on precipitation, especially in summer; two sources of atmospheric moisture (Gulf of Mexico and Gulf of California); interaquifer leakage; and recharge from intermittent streams with the flow-length expanding and contracting over large distances (tens of miles) depending on climatic conditions. Groundwaters in the southern part of the Basin seem to be, on the average, heavier in oxygen 18 by one per mil as

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Dr. Gary Landis and Mr. H. R. Northrop of the Geology Department, University of New Mexico, did most of the deuterium analyses used in this work. On repeated occasions, we were privileged to confer with them and observe them at work in their excellent laboratory. All of the oxygen 18 analyses, and a small number of deuterium tests, were performed by Geochron Laboratories of Cambridge, Massachusetts.

PROBLEM STATEMENT

A continued investigation of the Roswell artesian groundwater basin has furnished evidence of complex groundwater recharge and circulation patterns. Tritium activity in groundwater from many sampling points located in all parts of the Basin have been carried out over the last 25 years. They suggest that groundwater in the Basin is made up of 'fast' and 'slow' recharge components. The former consist of direct recharge from downward percolating precipitation or streamloss. 'Slow' recharge is believed to originate as precipitation along the Sacramento mountain front and is transmitted into the Basin proper by a variety of pathways (upward leakage from deep formations, springs discharging into streamchannels and subsequent streamchannel loss; lateral percolation through an unconfined aquifer). In addition to a regional aquifer system (regional water table and piezometric surface) one or more systems of perched localized aquifers have been recognized. They are the source of a large number (perhaps the majority) of springs in the Sacramento Mountains and along the mountain front and seem to play a major role in the recharge process.

The stable isotopes oxygen 18 and deuterium, which form part of the water molecule, undergo fractionation as atmospheric (meteoric) water condenses to form precipitation and then runs off along the surface of or percolates through the ground. Exchange processes between groundwater and aquifer rock may also alter the stable isotope makeup. Thus, the stable isotope composition may give important clues concerning the environment and climatic characteristics of groundwater formation and history of groundwater flow.

Purpose of this work was to establish baseline criteria for such a study and to attempt a broad interpretation of the data.

The detailed objectives will be introduced in the section on Stable Isotope Approach to Hydrology.

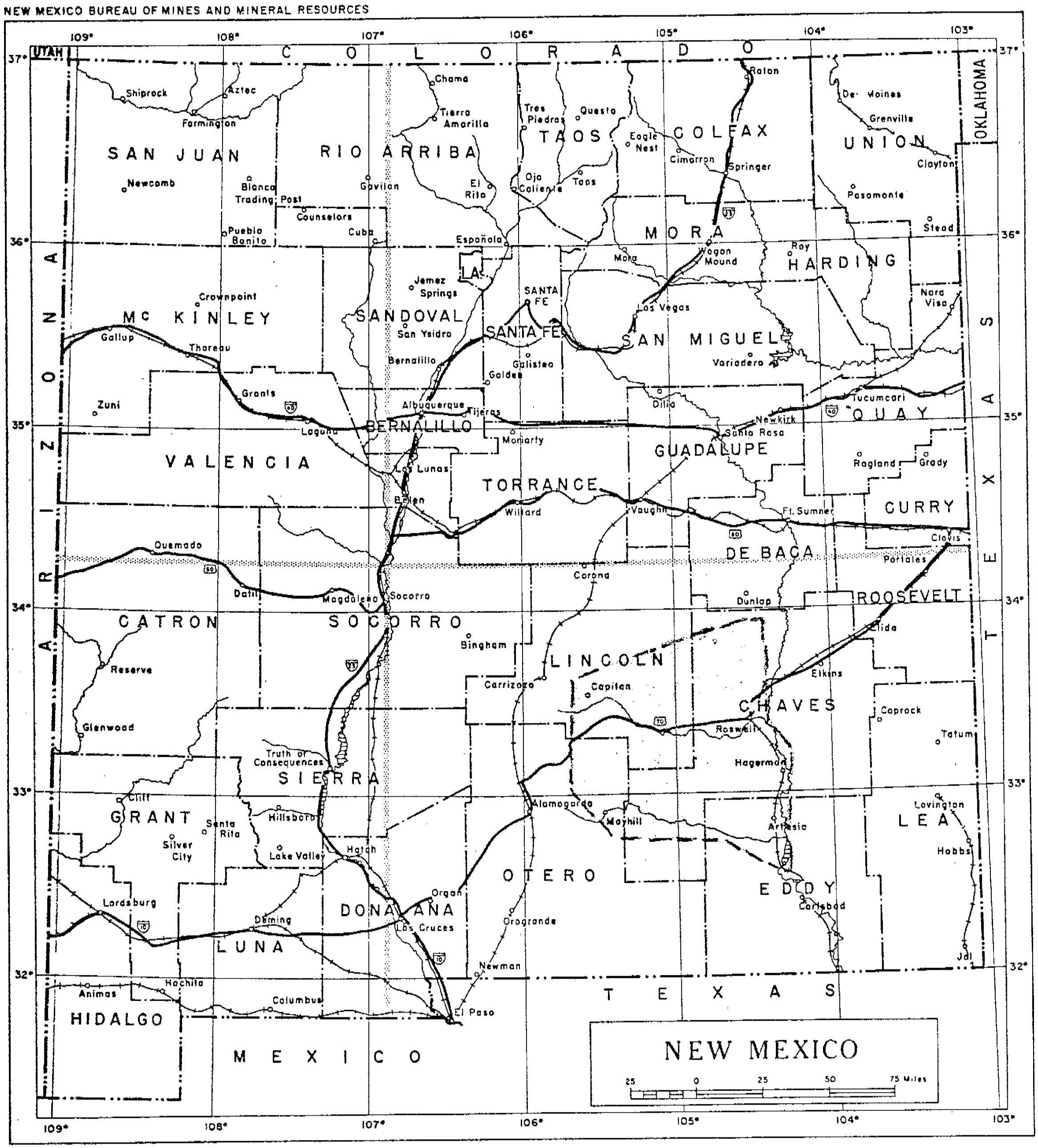

Figure 1: The study area and its location.

Blanca). The tributaries are, from north to south respectively, the Rio Hondo, the Rio Felix, and the Rio Peñasco. At the average elevation of 9000 feet in the Sacramento Mountains, the mean annual air temperature is 47°F (8°C). Precipitation again occurs as intense, localized thunderstorms, but winter precipitation, especially at the higher elevations, contributes a greater percentage than in Roswell to the annual total of up to 20 inches.

Geohydrology

The major geohydrologic divisions of the area follow the above defined geographic limits quite well (Figure 3). A simplified stratigraphic column for the basin in shown in Table I.

The Agricultural Belt

The narrow eastern strip is the primary artesian water source in the basin. The major aquifer, referred to as the Principal or the Carbonate Aquifer, is primarily in the Permian San Andres Formation which is encountered at depths from 400 to 800 feet below the surface in this region. In the study area, it is predominantly limestone and dolomite, with minor components of gypsum and sandstone. The Permian Artesia Group (shales, sandstones, evaporites, some carbonates) forms the confining to semi-confining layer on the San Andres, due to the large quantities of clay and silt in this group. In some portions of the basin, parts of the Artesia Group (formerly called the Chalk Bluff), notably the Grayburg, Queen, and Seven Rivers Formations, either form part of the

TABLE I. Simplified Stratigraphic Column for the Roswell Basin
(after Kelley, 1971, modified)

AGE	GROUPS, FORMATIONS, MEMBERS	DESCRIPTION
Holocene and Pleistocene	Alluvium	0-300 ft. thick Caliche, gravels, sands some clays
Pleistocene and Pliocene	Gatuna Formation	0-200 ft. thick Sands, clays, gravels, red color, thin layers of carbonates.
Permian	Artesia Group Tansill Formation Yates Formation Seven Rivers Formation Queen Formation Grayburg Formation	0-2100 ft. thick Upper portion: Clays, sands, evaporites. Lower portion: Clays, sands, carbonates. The Queen Formation is usually considered to form the aquitard.
	San Andres Formation Fourmile Draw Member Bonney Canyon Member Rio Bonito Member Glorieta Sandstone	250-1350 ft. thick Upper portion: Evaporites, sands (Lovington sandstone), carbonates (limestone, dolomite). Lower portion: Carbonates, sands (Glorieta Sandstone), shales.
	Yeso Formation	$\leq$ 1400 ft.

Precambrian

Note: Only those formations that outcrop are listed.

incorporated into the groundwater system. This is especially true of the three major rivers that cross the dipslope, the Hondo, Felix, and Peñasco. Fiedler and Nye (1933) proposed that this is the belt where most of the groundwater recharge occurs in the basin and called it the Principal Intake Area.

The Mountain Zone

Underneath the San Andres Formation, as one moves farther west to the Sacramento Mountains, two lower units become important. The Glorieta Sandstone, which is commonly taken to be a basal unit of the San Andres Formation, and the Yeso Formation gain importance due to their increasingly higher position and observed water producing potential, as evidenced by numerous springs (Davis, et al., 1980; Gross et al., 1979) and producing zones in the PVACD observation wells (Crawford & Borton, 1958; Gross et al., 1976). Until recently, the Yeso Formation was considered relatively unimportant as an aquifer (Fiedler & Nye, 1933; Mourant, 1963), but there is increasing evidence as to the long-term contributions of this formation (Davis, et al., 1980; Duffy et al., 1978). Mesozoic and Cenozoic volcanics and clastics outcrop elsewhere in the Sacramento Mountains, but their contributions to the overall hydrologic system of the basin are considered relatively unimportant.

Underlying Formations

Another geologic setting which has been considered relatively

Formation: on the order of 400 feet near Roswell to over 800 feet near Hagerman and Dexter (Gross *et. al*., 1976). The third structural relationship of importance is the presence of erosional unconformities between the Yeso and the San Andres and between the San Andres and the Artesia Group. These unconformities, combined with the collapsed, brecciated nature of the Yeso, the karstic nature of the San Andres, and solution features in all the units contribute to interaquifer leakage, variable hydraulic conductivities, and difficulty in defining confined and unconfined zones; all of which complicate characterizing the overall aquifer properties.

The Water Supply Problem and Previous Studies

Water Usage

Since 1950, over 100,000 acres have been under irrigation each year. Water consumption by the city of Roswell has been on the order of 10,000 acre-feet per year during the same time period. Water well levels have declined almost continuously from 1942, and the city of Roswell has moved some of its wells from north to southwest of the city to an area of better water quality, due to encroachment of saline waters north and east of the city. In truth, the term 'artesian basin' is no longer quite correct, since very few wells flow anymore, spring flow into the Pecos River has all but ceased, and the base flow of the Pecos River has dropped considerably. At the same time, water quality has been declining been studied in more detail by Havenor (1968) and by Kinney et al. (1968).

Through the years, the importance of a recharge contribution from the far western regions of the basin has been increasingly emphasized. According to this view, a substantial fraction of the artesian basin's groundwater enters the Principal Aquifer not by downward percolation of surface water (precipitation or surface runoff) but by upward leakage from the Yeso or possibly even deeper formations. Four recent studies (Gross et al., 1976; Duffy et al., 1978; Gross et al., 1979; Davis et al., 1980) have been particularly concerned with this problem. Tritium measurements throughout the basin and spectral analysis of the stream-aquifer recharge process in the central region of the basin provided evidence of 'fast' (i.e. water 'younger' than the tritium half-life of 12.4 years) and 'slow' recharge components and brought up the question of interaquifer leakage. Rehfeldt and Gross (1982) have suggested that this upward leakage may occur through fractures or faults, such as the three 'structure zones' mentioned earlier. The present work was undertaken with the hope that in investigation of stable isotopes in basin water would shed additional light on the processes of recharge and interaquifer leakage.

mass numbers of 1, 2, and 3, respectively; and for the oxygen isotopes, there are mass numbers 16 (^{16}O), 17 (^{17}O), and 18 (^{18}O). Table II shows the natural abundance of each of these isotopes. Tritium is an unstable (radioactive) isotope of hydrogen and is considered here with respect to previous studies of tracing and dating groundwater in the Roswell Basin (Gross et. al., 1976; Rabinowitz et al., 1977). Using only the stable isotopes, there are nine isotope combinations theoretically possible in a water molecule: $H_2{}^{16}O$, $H_2{}^{17}O$, $H_2{}^{18}O$, $HD^{16}O$, $HD^{17}O$, $HD^{18}O$, $D_2{}^{16}O$, $D_2{}^{17}O$, and $D_2{}^{18}O$. Molecules containing ^{17}O are generally omitted due to the relatively small amounts of ^{17}O present, and, in addition, only those molecules in which at least one ^{1}H atom is present need to be considered in natural occurrences, e.g.: $D_2{}^{16}O$ is disregarded.

The stable-isotope composition of a water sample is measured as the ratio of the heavy to the light isotope (i.e.: $^{18}O/^{16}O$ or D/H) and presented as a fractional difference with respect to a standard. This 'delta' notation will be introduced more formally in the section on EXPERIMENTAL TECHNIQUES.

Fractionation Factor

Since the thermodynamic properties of molecules depend upon the constituent masses, the similar molecules containing different isotopes separate slightly in changing environments. This separation is termed isotope fractionation, and the primary environmental factor is temperature. More precisely, the energy of a molecule is proportional to the temperature, but similar molecules with different isotopes will have slightly different energies at the same temperature due to nucleon and electron interactions. The internal energy of a molecule consists of contributions from rotational, vibrational, and electronic energies. Both rotational and vibrational energies are inversely proportional to the mass (actually the reduced mass) of the molecule. The contributions of the electronic energies are secondary to this discussion. As the temperature increases, molecules will have more energy, but the lighter molecules will have slightly higher energies, making them slightly more reactive (Daniels and Alberty, 1975).

Two types of reactions in which this isotopic fractionation is of interest are exchange reactions, such as the isotopic exchange of an ^{18}O for an ^{16}O atom between water and limestone, and physical processes such as evaporation and condensation of water vapor. A fractionation factor (α) is used to express the extent to which such reactions must go to attain equilibrium, *i.e.*:

The temperature dependence of the fractionation factor, resulting in a seasonal fluctuation of the isotopic composition, is best shown by an example. Starting with water vapor of a given ^{18}O composition, $\delta\, ^{18}O_v = -10^0/oo$, and the fractionation factor between water vapor and liquid,

$$\alpha = \frac{R_\ell}{R_v} = \frac{\delta^{18}O_\ell + 1000}{\delta^{18}O_v + 1000},$$

at 0°C, $\alpha = 1.0110$. Then

$\delta^{18}O_\ell = (1.0110)(-10^0/oo + 1000) - 1000 = 0.89^0/oo$. At 20°C, $\alpha = 1.0090$ and $\delta^{18}O_\ell = (1.0090)(-10^0/oo + 1000) - 1000 = -1.09^0/oo$. This would imply that, with isothermal condensation and equilibrium conditions, summer precipitation is isotopically lighter than winter precipitation, a condition not seen in nature. In fact, the converse is true. More realistically, condensation is the result of some kind of cooling process under non-equilibrium conditions. One of the most common non-equilibrium effects consists in the separation of the phases by "kinetic effects", i.e. motion (Dansgaard, 1964). For simplicity, the non-equilibrium process is assumed to be a Rayleigh process, i.e. slow condensation with the immediate separation of the condensate from the vapor after formation (Faure, 1977, p. 327). In such a process, the oxygen 18 content of the condensate decreases with decreasing condensation temperature (Dansgaard, 1964, p. 438-441 and Table 2). The non-linear increase of the fractionation factor with decreasing temperature requires that, under Rayleigh conditions, The "amount effect" (Dansgaard, 1964, especially Figure 21) is the observation that a heavy rainfall tends to be isotopically lighter than a light rainfall. This may explain part of the scatter of $\delta^{18}O$ values in precipitation at the two weather stations to be discussed. Reasons for the "amount effect" are complex and not well understood. Clearly, then, the isotopic composition of natural waters can provide a wealth of information about the water's history if the composition can be related to the controlling factors.

The complexity of the situation is obvious, even under simplified conditions. Fortunately, the condensation temperature is the easiest factor to take into account, and, in most instances, has more influence on the isotopic composition of precipitation than kinetic factors and other complications.

Evaporation not only affects the isotopic composition of precipitation, but it can also alter recharging surface water as it enters the groundwater system. The result is isotopically heavier water since the lighter isotopes evaporate more readily. In general, the effects of evaporation can be distinguished by simultaneous oxygen 18 and deuterium measurements because oxygen 18 is more affected by evaporation than deuterium. In a δD vs. $\delta^{18}O$ plot (Figure 9), the evaporation effect causes a flattening of the slope. This plot, and the so-called 'meteoric water line', will be discussed in the section on <u>Relationship Between Oxygen 18 and Deuterium Ratios</u> (p. 33).

temperatures do (that is, into the northeast quadrant of the δD vs. $\delta^{18}O$ graph and below the meteoric line). Where the exchange is slight it can, therefore, not be easily separated from evaporation and climatic effects. Such an exchange with clay and evaporite minerals was suggested by Lambert for certain groundwaters (brines) of the Delaware Basin (Lambert, 1978, see especially his Figure 3). The Roswell Basin has large amounts of marine shales and evaporites in its geologic column (Table I). They occur in all of the formations that are aquifers in the basin but are especially prominent in the Yeso. Such exchange processes would therefore be very much within the realm of possibility. Neither the geochemical characteristics nor the isotope values of the waters investigated for this report indicate, however, that such exchange processes with marine shales or evaporites have, in fact, taken place.

History Effects

This term designates peculiar isotopic ratios in natural waters reflecting exposure to past environments, especially climatic conditions, different from the ones in which the waters are presently found. For example, brackish groundwaters in Southern Israel "reflect the inflow of meteoric water that occurred during the humid Pleistocene" (Issar, 1981). No such effects can be inferred from our data.

Based on the results to be presented here, we believe that the groundwaters investigated for this report purely reflect the of river discharge, evapotranspiration, evaporation and precipitation in the basin. On the basis of isotope indices, the relative proportions (mixing ratios) of recharge sources (precipitation and stream losses) were computed.

Dincer et. al. (1970) studied snowmelt runoff in a small basin in northern Czechoslovakia using snowpack measurements plus tritium and oxygen 18 data. They were able to determine the contributions of meltwater to surface runoff and to subsurface water, and residence times for subsurface storage in the basin. Based on the success of the study, they hoped to stimulate the use of isotope techniques in snow hydrology.

Dincer and Payne (1971) studied the southwestern karst region of Turkey and successfully established the existence of a hydraulic link between inland lakes and coastal springs. This study is of great interest because they determined two flow components in the reservoir, a seasonal flow through solution features and a slower base flow. This situation is somewhat analogous to the condition thought to exist in the Roswell Groundwater Basin.

One of the most comprehensive isotope studies is that by Arnason (1976) in Iceland. All hydrologic systems were considered, with particular emphasis on the geothermal areas. The extensiveness of this study provides a reference for almost any isotope hydrology study.

results suggested that deep leakage, from aquifers beneath the San Andres Formation, supplied a significant fraction of groundwater recharge to the Basin. The use of stable isotopes was, therefore, to confirm and supplement the results.

A definitive answer to the first question would require pronounced differences in the isotopic signatures of groundwaters from different formations, of water from surface streams crossing the study area, and of precipitation.

For an answer to the second question, precipitation over the warm, semiarid dipslope should be isotopically heavier than that falling in the mountains to the west, and this difference would have to be reflected in the groundwater receiving recharge from this source.

The existence of "fast" and "slow" recharge components would be supported by an isotopic composition of groundwater intermediate between surface flow in the Principal Intake Area and groundwater from the deeper aquifers to the west of the latter.

These relations would be obscured by (1) exchange reactions with aquifer matrix material and (2) mixing of groundwater components of different origin. Appreciable matrix interaction has been ruled out above. Mixing remains to be considered.

are being drilled; few recent samples were therefore, readily available.

Fortunately, the State Engineer Office in Roswell and the New Mexico Bureau of Mines and Mineral Resources in Socorro have drill cutting 'libraries', and these may be used in the future. Once these offices have completely evaluated the cuttings, only small quantities of each depth interval of the cuttings are kept. Extensive utilization of these samples was postponed until after the completion of this preliminary study, because the determination of the ^{18}O content in a carbonate sample renders the sample unsuitable for future use. The State Engineer Office graciously allowed us to have portions of the cuttings from depth intervals we selected of the PVACD observation wells, and these will be evaluated after this preliminary study, if it is warranted.

The carbonate samples for this study were mainly from roadcuts at various locations in the Basin, with the addition of drill cuttings from one shallow well in the eastern portion of the Basin. The main concern in using samples from roadcuts was that surface exposure would alter the isotopic composition of the samples, resulting in misleading information; however, as discussed under RESULTS, this did not seem to be the case. In all the roadcut samples, care was taken to insure that large blocks of rock material were obtained such that interior portions of the blocks, not in direct contact with the atmosphere, could be chiseled from the blocks.

ions of mass 3, therefore, a correction is required to eliminate the influence of the T^+ ions (Kirshenbaum, 1951). The sample ratio is compared with a known standard, and the results are converted to per mil values, as for the oxygen results:

$$\delta D = \left[\frac{(D/H)_{sample} - (D/H)_{SMOW}}{(D/H)_{SMOW}} \right] \times 10^{3\,0}/oo .$$

Use of this notation yields values of δD for meteoric waters ranging from $+60^{0}/oo$ for isotopically heavy samples to $-300^{0}/oo$ for isotopically light samples (Craig, 1961 b).

deuterium in Basin waters and its interpretation in terms of recharge processes and hydrologic circulation patterns.

Relationship between Oxygen 18 and Deuterium Ratios

Using the assumption of Rayleigh conditions, it may be shown (Dansgaard, 1964) that an essentially linear relationship should exist between the δD and $\delta^{18}O$ values in water samples of atmospheric origin, with a slope of 8.0. Using some 400 meteoric and surface water samples, Craig (1961b) established the straightline relationship $\delta D = 8\delta^{18}O + 10$. This is commonly called the 'meteoric waterline'. The intercept is called the 'deuterium excess'.

In some natural processes, this relationship does not hold true, thus, by plotting the δD-$\delta^{18}O$ graph for an area of interest, differences in the behavior of the two isotopes may be investigated. Perhaps the most spectacular example of such contrary behavior is the "oxygen-isotope shift" of geothermal waters. Their deuterium values are in line with those of local meteoric water, however, the oxygen 18 values are shifted to values more positive than those of local precipitation by $5^{o}/oo$ to $20^{o}/oo$ in some instances, due to increased reaction with carbonate and silicate rocks at the higher temperatures (Faure, 1977). Since no such effects have been noted in the Roswell Groundwater Basin, this shift should not be observed, but evaporation effects which result in a shift of both oxygen and deuterium ratios, might become apparent because of the warm, dry climate. Based upon theoretical and experimental results

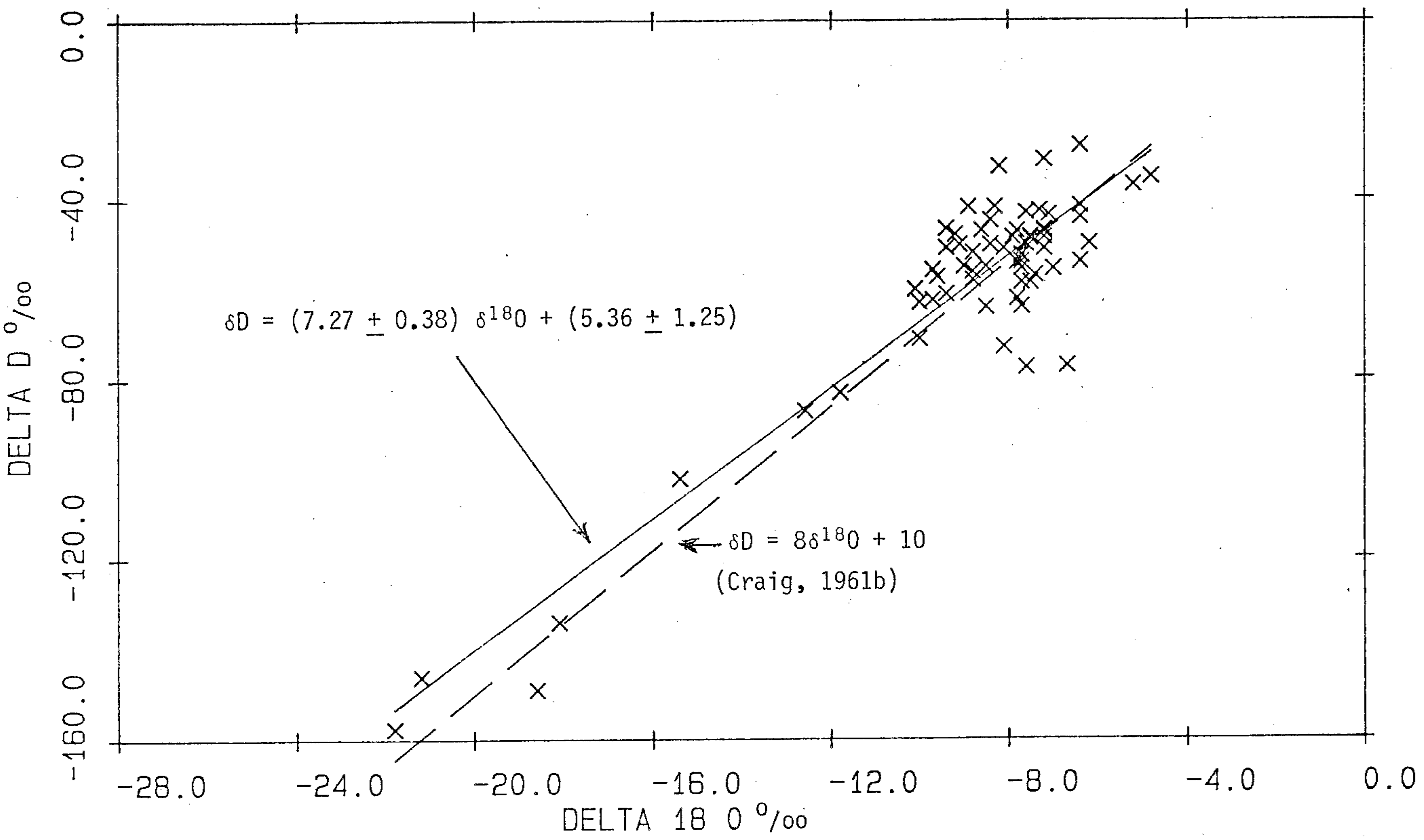

FIGURE 4: δD - $\delta^{18}O$ scatter plot and simple least-squares fit.

this basin to other areas and for obtaining data for time periods when no samples were available. The second relationship is necessary for comparing groundwaters with the assumed source of recharge.

Two NOAA weather reporting stations in the basin provided precipitation data, precipitation samples, and temperature data. Weighted mean $\delta^{18}O$ values (with respect to SMOW) were determined for systematic precipitation samples collected from 1976 to 1978. The stations were conveniently located, one in the western portion near Elk, NM. (5,700 ft. a.m.s.l.) and the other in the eastern portion at Roswell (3,669 ft. a.m.s.l.). This allowed analysis of data from two of the geographic zones within the basin: the 'producing' zone in the Pecos River Valley, and the western edge of the Principal Intake Area in the foothills of the Sacramento Mountains. Continual precipitation samples were not available from higher altitudes, but snow samples were collected to measure isotopic composition of winter precipitation which would influence the snowmelt composition.

Monthly or bimonthly composite precipitation samples were used for two reasons: (1) to insure adequate sample size for all the analyses since precipitation amounts for individual storms vary from traces to several inches; and (2) to smooth the effects of varying ^{18}O content among individual storms. Table III shows comparisons of smoothed and unsmoothed ^{18}O values. Usually, 500 milliliters of composite sample were prepared with water from all storms in the time period covered.

Two temperature values were used, one of which was the average temperature from the whole month and the other of which was an average of the temperature on the days when there was a precipitation event for which we had a sample. This average of event-day temperature probably corresponds more closely to the condensation temperature which is a dominant variable affecting the ^{18}O content of the precipitation.

The temperature and precipitation data from the two stations over a three year time period are compiled in Tables A2 and A3.

A relationship between air temperature and ^{18}O content, such as that described by Dansgaard (1964) was established to determine how these precipitation values compare with those from other locations and to compute ^{18}O values for time periods for which a precipitation sample was not available. To determine the relationship, plots of $\delta^{18}O$ vs. temperature were constructed. At first, the overall monthly temperatures were used, but, since precipitation events are few and far between and temperatures fluctuate considerably in a given time period because of the climatic characteristics of the basin, the average of event-day was compiled. Using the two different temperature sets, the plots of $\delta^{18}O$ vs. temperature values were not markedly different, but when a linear least squares regression was applied, there was some improvement in the 'fit' of the line using the average of event-day values. These plots and their equations are shown in Figures 5,

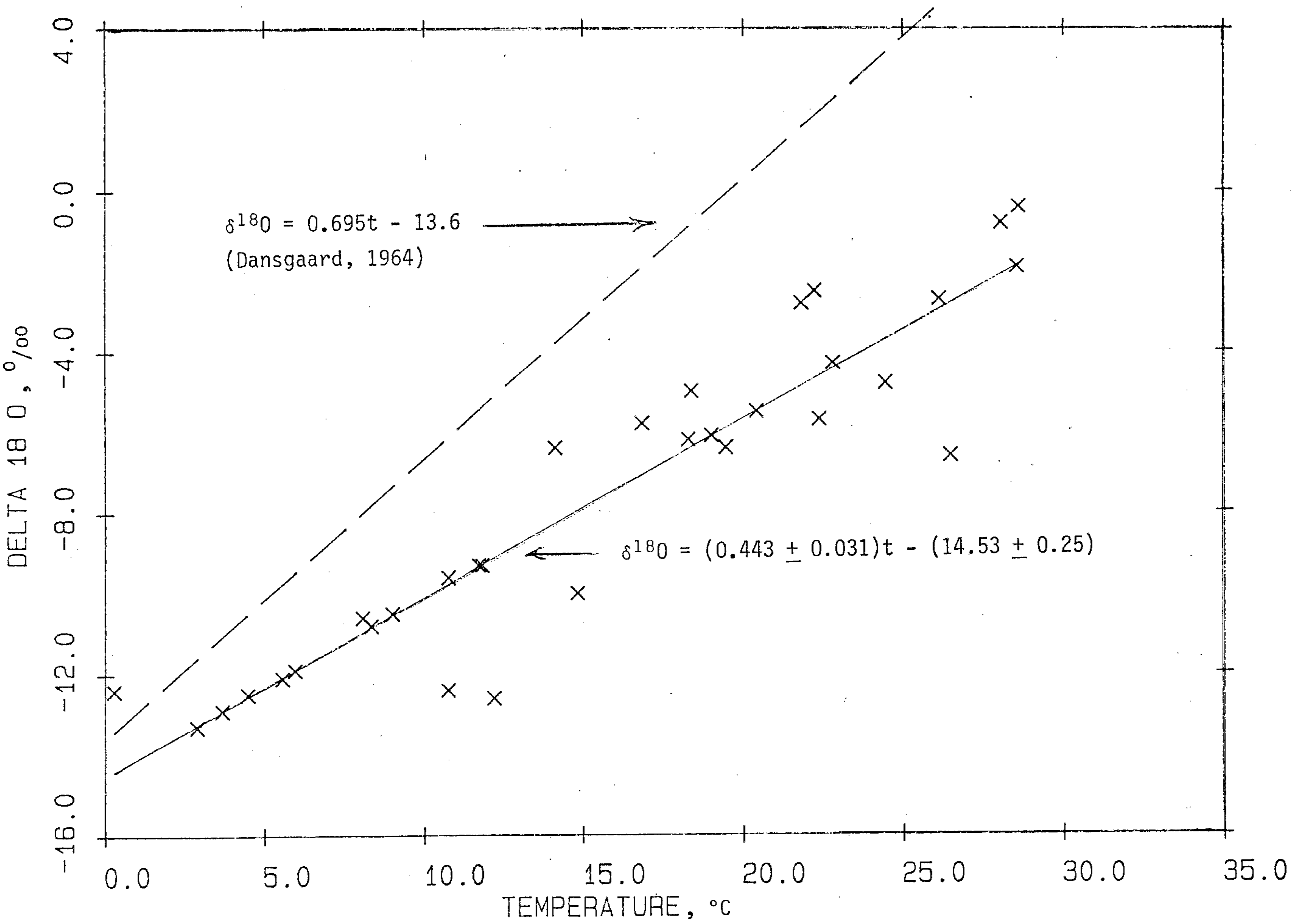

FIGURE 5: $\delta^{18}O$ vs. 'condensation temperature'. Roswell.

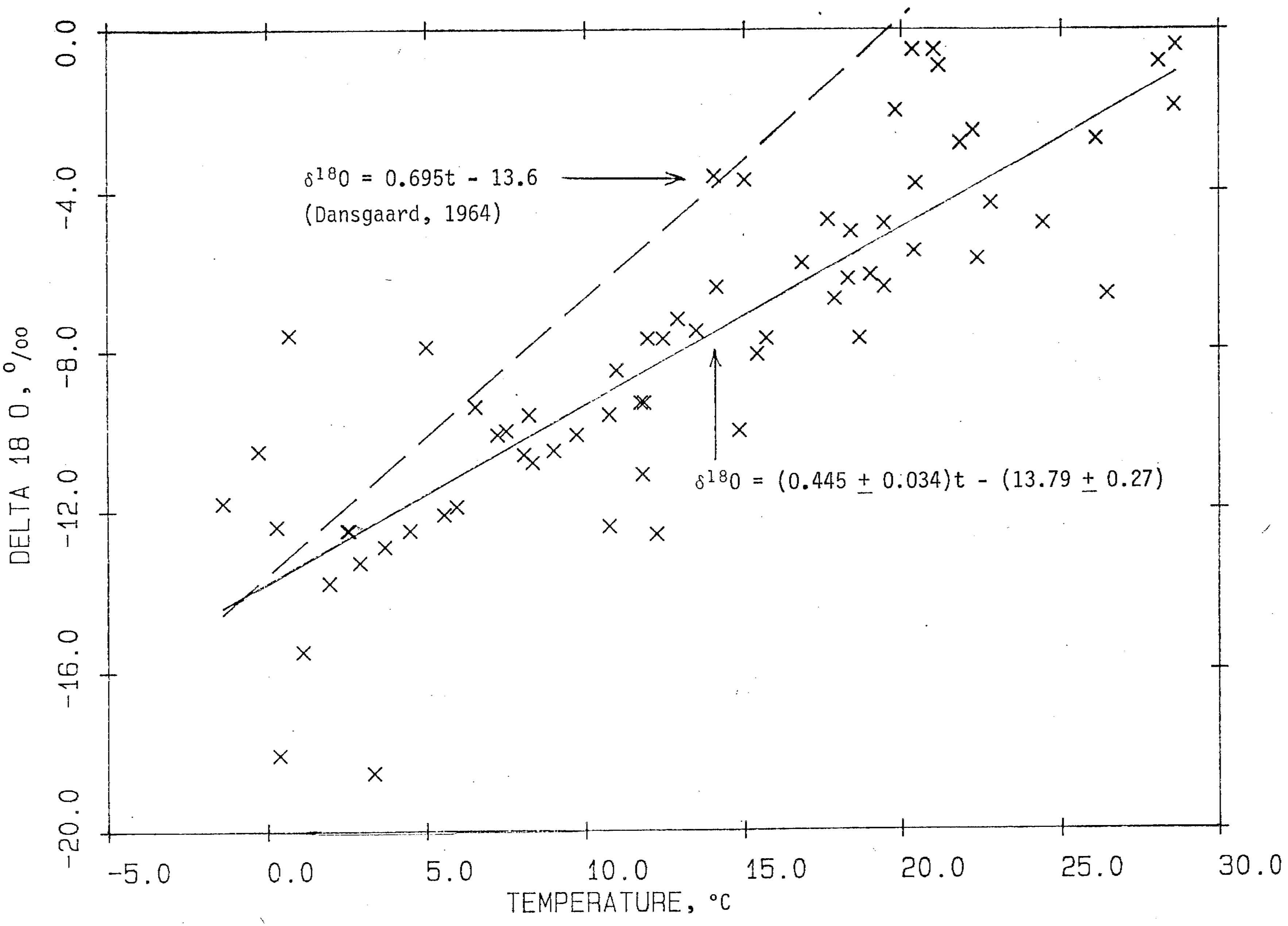

FIGURE 7: $\delta^{18}O$ vs. 'condensation temperature'. Roswell and Elk.

comparison, Dansgaard (1964, Table 10) gives a range of -16^{o}/oo to 0^{o}/oo for Flagstaff, Arizona, and -19^{o}/oo to -2^{o}/oo for Chicago, Illinois. Thus, the range and numerical values given in Tables A2 and A3 seem to be fairly typical in comparison with other regions of the central and southwestern United States.

These precipitation samples were not originally collected for the purpose of stable isotope determinations. They came from rain gauges of the weather reporting stations and, although collected into stoppered bottles as soon as possible, they may have undergone some evaporation on occasion. Given the internal consistency of the weighted results shown above, this error is believed to be small.

All but two of the snow samples taken for this survey were from snowpack, not fresh snow. Some samples included the top crust of snow, others did not, and some, such as the sample from St. James Campground, were leftover patches of ice. The isotopically light nature of these samples indicates that, while evaporation may have occurred, it was not sufficient to render melted snow indistinguishable from the lightest rain at Roswell.

Oxygen Isotope Fractionation between Limestone and Water

Six limestone samples were anlayzed for their $\delta^{18}O$ content to determine if the groundwater samples are in isotopic equilibrium with the primary aquifer material. The results of the analyses are shown in Table A4.

(2) the appropriate equation for the equilibrium constant is: (Faure, 1977, p. 336)

$$K = \frac{([CaC^{18}O_3] \ / \ [CaC^{16}O_3])^{1/3}}{[H_2{}^{18}O] \ / \ [H_2{}^{16}O]} \equiv \frac{R_c}{R_w}$$

where: K = isotope fractionation factor.

It can further be shown (Faure, 1977, p. 336) that the equilibrium fractionation factor for water and limestone is:

$$K = \frac{R_c}{R_w} = \frac{\delta^{18}O_c + 1000}{\delta^{18}O_w + 1000} ,$$

where R_c, R_w are the $^{18}O/^{16}O$ ratios for carbonate and water, respectively.

Clayton (1961) gives the equilibrium fractionation factor as 1.02855 at 25°C. This value is adequate for a rough estimate because the fractionation factor does not vary much in the expected range of surface temperatures in the Basin. Since, moreover, temperature on the average only increases 1°C per 30 meters of depth (Condie, 1976) it is also acceptable at depths studied in the Basin (500-1000 ft). Using the high and low $\delta^{18}O$ values measured in the limestones, the theoretical ^{18}O content of groundwater in contact with similar limestones may be calculated:

(1) from the low value ($25.04^{o}/oo$):

$$\delta^{18}O_w = \frac{25.04 + 1000}{1.02855} - 1000 = -3.41^{o}/oo$$

The river waters are isotopically light for the Hondo drainage system, on the order of -9^{0}/oo, in comparison with expected precipitation (using the -7.1^{0}/oo value of Elk), but they are in line with expected precipitation values at altitudes higher than Elk, and with snowmelt contributions (see Miscellaneous Snow Samples in Table A1).

The next major Pecos tributary south of the Rio Hondo is the Rio Felix. The samples show isotope contents similar to those along the Hondo. One would expect the April sample to be lighter than the July sample rather than vice versa as shown; the groundwater system in this sampling area, the Flying H Ranch, may be an independent system, since all the wells in the area are flowing wells. It contributes substantially to the surface runoff. A comprehensive study of the area would clarify the situation, but for this study it is sufficient to note that the Rio Felix waters are isotopically similar to those of the Rio Hondo.

The last major Pecos tributary in the study area is the Rio Peñasco. The oxygen 18 values are on the order of -9^{0}/oo to 10^{0}/oo in its upper course, but these values appear more consistent than for either of the other two tributaries. This is probably because of the effluent nature of the stream, with springs contributing greatly to the base flow of the river in its upper reaches. The river sample at Mayhill is essentially a sample of Posey Spring, a large regional spring system just upstream from the sample site.

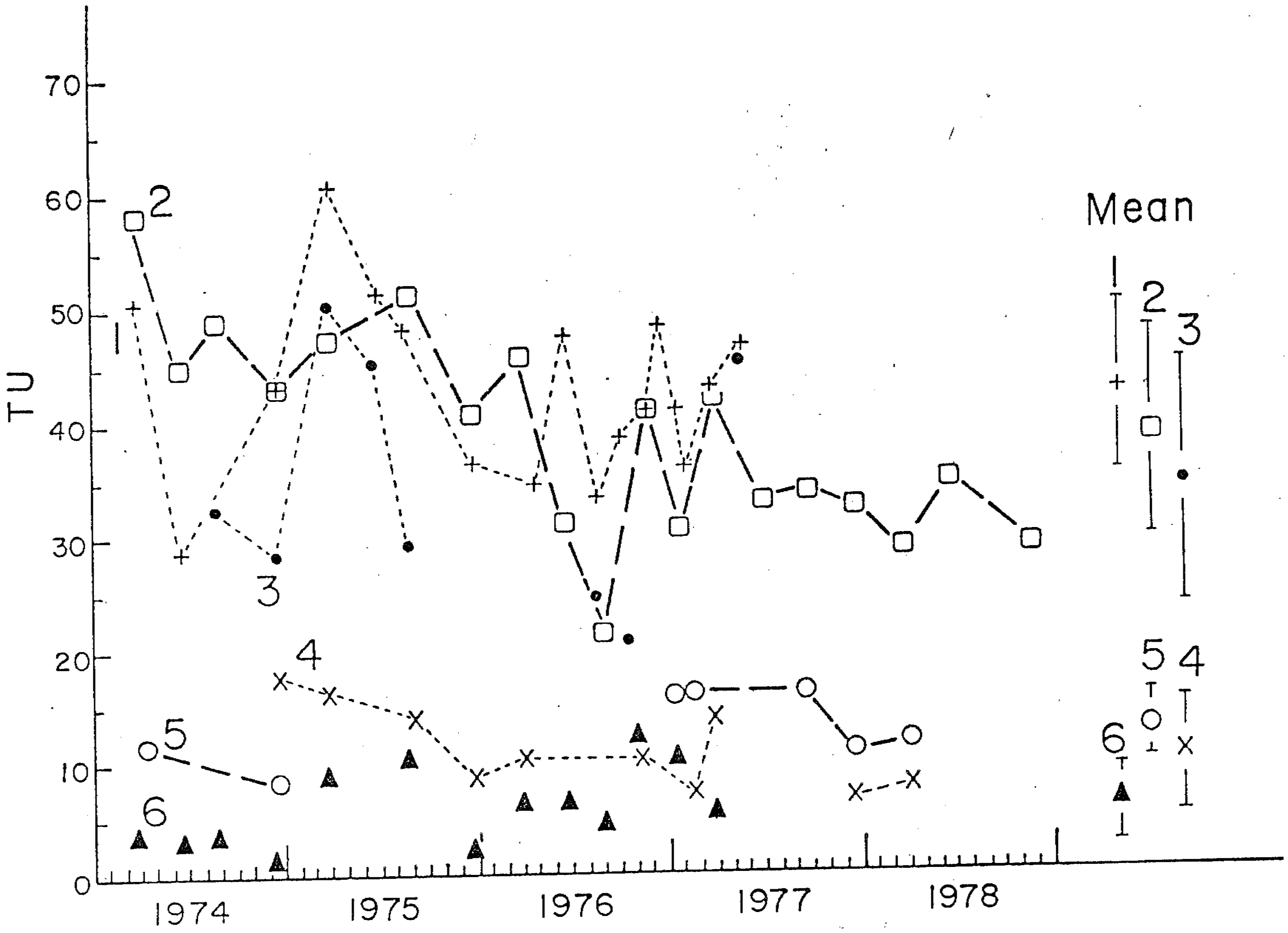

Figure 8: Groupings of natural waters according to tritium activity. Principal Recharge Area. Typical counting standard deviation of individual data points is ±1 TU. For individual samples, see Gross and Hoy, 1980. 1 = Rio Ruidoso at Hondo; 2 = Observation well 8; 3 = Rio Bonito at Hondo; 4 = Rio Peñasco at Observation well 7; 5 = Observation well 7 (no data for 1975/76 because of cave-in); 6 = Observation well 2.

channels in the form of springs. A hydrogeologic study of springs has revealed important features of recharge processes and groundwater circulation patterns in the Basin (Davis et al. 1980).

Waters from only five springs were analyzed for this study. Two of the springs, Paul Spring and Cleve Spring, are located within five miles of each other in the southwestern part of the study area. Trout Farm Spring is located in the northwestern part of the area, and Boiling Spring discharges into the Pecos River in the most southeasternly portion of the study area. Macho Spring, located north of the Capitan Mountains, discharges into the Macho drainage.

There are marked differences in the oxygen 18 values among the springs. The two springs in the southwest show oxygen 18 values on the order of $-6.0^{o}/oo$ to $-8.6^{o}/oo$ with a mean of $-6.8^{o}/oo$. It was expected that both these springs would show similar values due to their proximity and similar geologic setting. The systems feeding these springs are considered small perched systems near the Yeso/San Andres contact which should reflect local precipitation, and perhaps are a little heavier due to evaporation during infiltration. They are typical of many spring systems in the mountain zone. The weighted mean precipitation for the Elk weather station, which is just across the Rio Peñasco from Paul Spring, is $-7.1^{o}/oo$, in the range of the spring values.

as a perched system, it seems to be more extensive than either of the above two springs, the discharge is larger, Yeso outcrops are more extensive in this part of the Basin, and it may have a larger component of snow melt from Sierra Blanca in its recharge. Any or all of these factors may be reflected in the lighter oxygen 18 values.

Macho Spring had the lightest $\delta^{18}O$ value measured for any spring. This may reflect its relation to the regional artesian groundwater system (Davis et al., 1980, p. 31). It derives its discharge from deep percolation which comes from the Capitan Mountain massif, (10,179 ft a.m.s.l.) an intrusive stock or laccolith (Kelley, 1971, p. 42).

The importance of these western spring measurements is their apparent correspondence to local precipitation and overall uniformity in time.

Boiling Spring in the southeast is isotopically very heavy, $-2^{0}/oo$ to $-3.4^{0}/oo$, in comparison with most oxygen 18 measurements in the Basin. There are two possible explanations. The more probable explanation is mixture with river water and evaporation due to restricted circulation in the small 'cove' in which the spring is located (see Figure 9). At Artesia, approximately twenty miles upstream from the spring, the river water measured $-5^{0}/oo$. The other possibility is that the spring may issue water which has resided in the San Andres long enough to exchange responded rapidly to runoff events in the nearby rivers Peñasco and Hondo, respectively. The remaining five wells, located in the interfluvial highlands of the San Andres dipslope, show mainly slow, long-term changes in water levels. Tritium determinations (Table A1) show that 08 reflects direct recharge of Hondo stream water ($\geq$29 TU). 07 also is controlled by direct recharge from the Peñasco but since the Peñasco runoff has a large groundwater component, the TU values are lower (10-16 TU). As illustrated in Figure 8 and discussed earlier, tritium ratios of these two observation wells fall squarely within the range of tritium activities of their respective recharge sources. Samples from the other observation wells are lower still in tritium, suggesting an absence of direct recharge. These relationships are not clearly reflected in the $\delta^{18}O$ values. The grand mean of all observation wells is $-8.1^{o}/oo$. This compares to $-8.6^{o}/oo$ for the other Intake Area wells (see below). The difference may be fortuitous or it may reflect some evaporation along the casing in the static (that is, no artificial flow induced by pumping) observation wells. In any case, these values seem to fall in the range characterizing recharge from the mountain zone. 02, 03, and 07 are slightly higher ($-7.4^{o}/oo$ to $-7.5^{o}/oo$). In the case of 07, this may either reflect evaporation of the river water during the recharge process, or it may be attributed to the generally slightly heavier character of groundwater in the southern part of the basin, as will

Generally speaking, recharge to the northern wells (Arroyo del Macho and Rio Hondo drainage systems) seems to include more contributions from higher altitudes than recharge to wells near the Peñasco. The Rio Hondo drainage includes Sierra Blanca (11,977 ft a.m.s.l.), highest peak in the Sacramento Mountains, in its source area. Arroyo del Macho drains the northeast side of the Capitan Mountains (10,179 ft a.m.s.l.). The Peñasco drainage basin includes vast highlands of somewhat lower elevation. As investigated elsewhere (Rehfeldt and Gross, 1982), deep leakage (from underlying aquifers, notably the Yeso Formation) supplies a significant fraction of the groundwater, and the isotopic composition of this source is presumably determined by the elevation of its outcrops along the Sacramento-Sierra Blanca-Capitan mountain front.

Principal Aquifer Wells in the Confined Zone

East and south of Roswell, where the Principal Aquifer is in close hydraulic connection with the alluvial aquifer immediately overlying it (the Artesia having largely been eroded away), the signals are mixed.

Three saltwater wells east of Roswell (Elk #1, Conservancy, and Roswell Saltwater Treatment Plant) range from $\delta^{18}O = -7.6^{o}/oo$ to $-8.9^{o}/oo$. $\delta^{18}O$ values of the flowing irrigation wells of the Clardy group southeast of Roswell range from $-4^{o}/oo$ to $-8.8^{o}/oo$, with a mean of $-7.1^{o}/oo$. Allison RA 1102 south of Roswell showed is located close to Havenor's (1968, Plate 1) K M Fault. It is within the Rio Felix drainage basin, as are three Principal Aquifer wells north of this location (Villa Solano, Hagerman, Jake Johnson). Principal Aquifer wells in and south of Artesia belong to the Rio Peñasco drainage basin and show a similar range (i.e. between $-7^{0}/oo$ and $-8^{0}/oo$), with two exceptions: the Gates well shows a spread of $\delta^{18}O$ values from $-5.4^{0}/oo$ to $-8.6^{0}/oo$ (with a mean of $-6.5^{0}/oo$). This is probably the result of mixture with Alluvial Aquifer water in variable proportions. The Alluvial Aquifer is not cased off. The deep Vandiver well, in which the Alluvial Aquifer is cased off, ranges from $-8.4^{0}/oo$ to $9.2^{0}/oo$. It derives its production exclusively from the San Andres.

Alluvial Aquifer Wells

The Alluvial Aquifer wells in the Hagerman-Artesia section show a wider spread of $\delta^{18}O$ values and are, on the average, isotopically heavier (from $-3.6^{0}/oo$ to $-8.6^{0}/oo$ with a mean of $-7.0^{0}/oo$ or $-7.3^{0}/oo$). This is the result of evaporation which especially affects irrigation returns (see, e.g., the hand dug windmill well with $\delta^{18}O = -3.6^{0}/oo$) and of direct recharge to the Alluvial Aquifer at the lowest elevations in the basin. In this southern section of the basin, the Principal and Alluvial Aquifers are hydraulically isolated from each other, but leakage along well casings and mixing within wells nominally pumping from the Principal Aquifer may mask the true isotopic composition of Principal that estimate the fast recharge contributions at less than 50% of total recharge (Gross et al., 1979; Rehfeldt and Gross, 1982; Wasiolek and Gross, in preparation).

The Artesia area wells have never displayed the tritium peaks observed in the Roswell area. This has been attributed to a lower transmissivity in the southern part of the basin (Rabinowitz et al., 1977).

Circulation Patterns and Related Effects

We now return to the δD vs. $\delta^{18}O$ relation, shown in Figure 9. Minor evaporation effects are noticeable in the departure from the meteoric line of some precipitation, as well as of spring and surface samples in the northeast quadrant of the graph. Precipitation is fairly well spread out over the whole usual range of Craig's meteoric line, with snow being isotopically lightest (southwest quadrant), as expected. This reflects the orographic and climatic diversity of this extensive basin. Groundwater samples (including springs) fall, however, into a relatively narrow range, roughly: ($\delta D = -30^{o}/oo$ to $-80^{o}/oo$ and $\delta^{18}O = -5^{o}/oo$ to $-10^{o}/oo$). This range is comparable to that measured by Lambert (1978) in the Delaware Basin. It indicates a meteoric origin unmodified by aquifer matrix interactions.

Because the groundwater data are crowded in such a narrow range ostensibly falling within the isotopic composition of precipitation at lower to intermediate elevations in the basin, it could be argued that, in fact, these data support the classical concept of groundwater recharge predominantly originating by summer precipitation and runoff in the Principal Intake Area. This conclusion is at variance with the tritium data (Figure 8, see also Gross et al., 1976), as well as with other hydrologic evidence (e.g.: Gross et al., 1976; Duffy et al., 1978; Gross and Hoy, 1980; Rehfeldt and Gross, 1982). Moreover, the Elk weather station is located outside of and higher than the Principal Intake Area, yet summer and fall precipitation at this locality considerably overlap with Roswell (where winter precipitation is very infrequent). As we have seen, the mean oxygen 18 content at Elk is somewhat lighter than at Roswell. For all these reasons we feel justified in looking to alternative ways of explaining the isotopic composition of groundwater in the basin. A brief outline follows.

A homogeneous δD-$\delta^{18}O$ distribution in groundwater, such as observed in the present case, is usually considered evidence of thorough mixing in the aquifer (Conrad et al., 1978) or of a very localized recharge source (Gallo, 1978). In our case, mixing is reasonable because the flowpaths are long. There are other factors that promote mixing. In years of ample moisture at the higher elevations, rivers flow farther east and contribute recharge over a larger area. In dry years, smaller surface flows are incorporated further to the west and must percolate through more limestone to reach the discharge zone. The southern rivers (Felix and

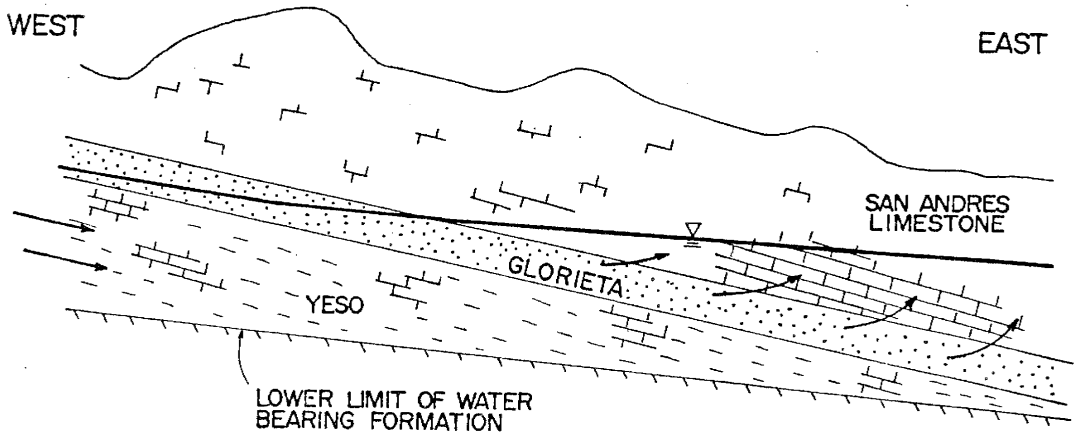

Figure 10: Diagram illustrating the concept of recharge to the Principal Aquifer in the San Andres Formation by upward leakage from underlying formations.

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during precipitation. The smaller hydrogen excess (5.5^0/oo vs. 10^0/oo) is believed to be statistically insignificant because of sampling deficiencies.

(3) A systematic relation was found to exist between condensation temperature and oxygen 18 content of precipitation. This relation is somewhat weaker than that established by Dansgaard for more northerly latitudes.

(4) Similarly, the dependence of oxygen 18 on elevation, though systematic, is somewhat weaker than in more temperate climate.

Next, it was necessary to ascertain whether surface and groundwater had undergone significant evaporation during surface storage, runoff or percolation. Such effects were observed in only a few specific cases that have been discussed.

The limestone analyses and appropriate calculations indicate that no appreciable isotope exchange has occurred between groundwater and aquifer matrix. Apparently, groundwater does not reside in the system long enough for such reactions, as verified by tritium results. Even the deepest recharge sources may be too shallow for significant exchange reactions with bedrock to have taken place. Nothing like the highly atypical saltbrines reported by Lambert (1978) from the Carlsbad area, indicative of intense isotopic exchange between water and evaporite bedrock, seems to exist in the Roswell Basin. Groundwaters in the Roswell Basin, therefore, represent present climatic conditions.

RECOMMENDATIONS FOR FUTURE WORK

In the course of this study, numerous possibilities for future directions have become apparent.

Systematic sampling should be continued to resolve ambiguities of the interpretation and improve the data base where deficiencies have become apparent. For example, how significant is the observed difference in mean oxygen 18 weight between northern and southern groundwaters, and between the latter and the rivers Felix and Peñasco. Renewed sampling in space and time should be systematic and be guided by statistical principles.

Precipitation from the extreme western portion of the basin, to complement the Roswell and Elk weather data, would improve the profile of isotope input in water across the Basin. While the miscellaneous snow samples provided some information, more quantitative and continuous data would be helpful and could possibly be obtained at Ruidoso or Cloudcroft. Similarly, groundwater from the mountain zone needs to be investigated more systematically.

The sampling of groundwater at more locations would improve the profile of groundwater isotope variations. Four locations of interest for which water samples are readily available are: (1) shallow wells in the Roswell area, (2) wells of more appropriate construction in the Artesia area, (3) wells far from the major drainage systems, and (4) Macho Spring at the head of the Arroyo del Macho. This location is in an area

Ch. 18). A wide range of salinities is observed in the Roswell Basin, and such a study in the basin could prove interesting. Evaporation is usually the basis for the correlation, and, while evaporation has not been proven significant in this preliminary study, a more detailed study would be necessary. Also related to salinity, the isotopic composition of the brines encroaching from the northeast could provide information on the rate of encroachment and the sources of the brines. This might also lead to information on the presence or absence of water in the pre-Yeso formations.

In line with studying the waters in the pre-Yeso formations, more geologic information would be necessary for interpretation. In terms of interaquifer leakage and a 'slow' recharge component, it seems imperative to understand the hydrologic behavior of these lower formations.

The list of possibilities becomes self-generating at this point, but the above suggestions seem the most feasible and would contribute the most to understanding of the Roswell area and the general applications of isotope hydrology to the solution of problems in this basin.

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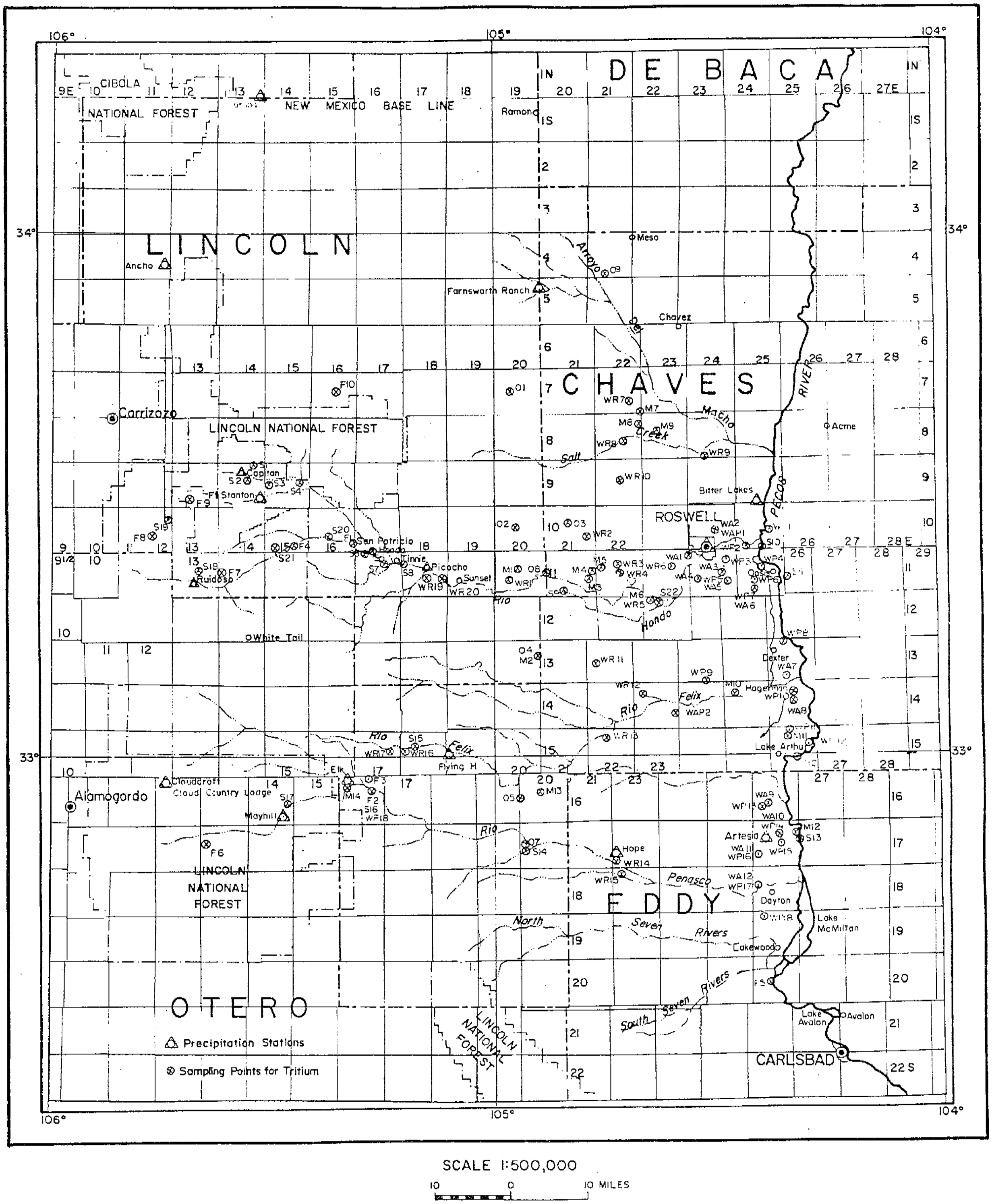

Figure A1: Sampling points for tritium and for stable isotopes. This map shows all sampling points, including many that were not used for this report.

Table A1

Roswell Groundwater Basin
Oxygen 18, Deuterium, and Tritium Analyses of Water Samples

Type of samples	Map #	Sample Location	Sample #	Date Collected	$\delta^{18}O$ $^{o}/_{oo}$	δD $^{o}/_{oo}$	Tritium (T.U.)
Springs	F1	10.17.29.4143	2800	3/19/78	-8.3	-41.8	6.9±0.7
		(Trout Farm Spring)	1264f	11/16/78	-8.1	-51.1	
	F3	16.16.02.323	2368	5/5/77	-6.2		6.4±0.8
		(Cleve's Spring)	2539	1/14/78	-7.4		3.6±0.6
		Mean of Cleve's Spring			-6.8		
	F2	16.16.11.342	2370	5/5/77	-6.0		3.5±0.7
		(Paul Spring)	2397	7/15/77	-6.5		1.5±0.9
			2398	8/17/77	-7.6	-43*	12.1±0.9
			2394	9/16/77	-6.4	-54*	5.4±0.8
			2404	11/20/77	-6.3		1.4±0.7
			2406	1/14/78	-6.4	-41.5	0.9±0.7
			2408	3/11/78	-6.3		2.0±0.8
			1439f	6/3/79	-8.6	-47.1	
		Mean of Paul Spring			-6.8	-46.4	
	F5	20.26.27.100	2435	9/17/77	-3.4	-38.5	39.1±1.6
		(Boiling Spring)	2563	4/1/78	-2.0	-30.0	34.6±1.6
	F10	7.16.7.43 (Macho Spring)	1414f	4/14/79	-10.0	-63.0	
Surface Water	S4	9.15.14.240	2565	6/25/78	-8.9		21.5±1.4
		(Rio Bonito @ Baca Campground)	2566	11/16/78	-10.1	-60.0	47.7±2.0
	S21	10.15.33.333	2564	6/23/78	-9.3		46.6±1.6
		(Rio Ruidoso @ Fox Cave)	2568	12/1/78	-9.7	-62.4	50.0±2.1
	S8	11.18.16.000	2513	6/23/78	-7.3		15.9±0.7
		(Rio Hondo @ R.O. Anderson Well)	2569	12/1/78	-10.1		41.3±1.6
	S9	11.21.29.400 (Rio Hondo @ turnoff to Obsv. Well #4)	2567	11/18/78	-8.8	-56.2	38.9±1.7
	S10	10.25.34.334 (Pecos R. @ Roswell)	2562	4/1/78	-12.6		40.7±2.0

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Type of samples	Map #	Sample Location	Sample #	Date Collected	$\delta^{18}O$ ‰	δD ‰	Tritium (T.U.)
Observation Wells (continued)	O7	17.20.18.434	2534	9/17/77	-6.9		16.0±1.1
		(P.V.A.C.D. #7)	2538	12/17/77	-6.8		11.1±0.9
			2530	4/2/78	-8.6		9.8±0.9
				Mean O7	-7.4		
	O8	11.21.18.333	766f	3/26/77	-7.3		42.1±1.6
		(P.V.A.C.D. #8)	839f	6/26/77	-7.5		33.0±1.3
			974f	9/18/77	-9.0		34.0±1.5
			1059f	12/18/77	-8.6		32.4±1.3
			1130f	3/19/78	-8.3		28.7±1.1
			2518	6/25/78	-8.9		34.9±1.5
			1278f	11/18/78	-7.5		29.0±1.3
				Mean O8	-8.2		
	O9	4.21.33.111	1205f	6/24/78	-8.9		3.0±0.6
		(P.V.A.C.D. #9)	1274f	11/18/78	-8.2		4.0±0.7
				Mean O9	-8.6		
		Mean of All Observation Wells			-8.1		
Intake Area Wells	WR19	11.18.15.313 (R.O. Anderson) domestic and stock	2514	6/23/78	-9.3		25.5±0.9
	WR3	11.22.09.321	2510	12/18/77	-9.4	-46.7	4.2±0.5
		(Woods Well) domestic and stock	2517	6/25/78	-8.9	-41.8	5.0±0.8
	WR5	12.23.06.441	2516	6/24/78	-9.3		2.7±0.5
		(Patterson 'Big Cat') irrigation		(pumping 391 gpm)			
	WR5	12.23.05.313 (Patterson 'House Well') domestic	2515	6/24/78	-9.2		15.9±0.7
	WR7	7.22.26.131	2525	3/18/77	-8.6		4.9±0.7
		(Tom Corn Well) stock	1268Bf	11/17/78	-8.7		4.2±0.6

Table A1

Roswell Groundwater Basin
Oxygen 18, Deuterium, and Tritium Analyses of Water Samples

Type of samples	Map #	Sample Location	Sample #	Date Collected	δ^{18}O $^{0}/_{00}$	δD $^{0}/_{00}$	Tritium (T.U.)
Principal Aquifer Wells (continued)	WP5	11.24.25.341	2519	3/25/77	-8.2	-32.7	5.5±0.9
		(Allison RA	2527	4/1/78	-7.8	-47.2	1.1±0.7
		1015/1012-S-Comb-B)		(pumping 1150 gpm)			
		irrigation					
	WP5	11.24.26.224	2507	9/17/77	-9.3		6.8±0.8
		(Allison RA 1102)		(pumping 1850 gpm)			
		irrigation	2511	4/1/78	-9.5		2.6±0.7
				(pumping 1800 gpm)			
	WP9	13.24.34.441	1160f	4/1/78	-7.2	-31.1	
		(Villa Solsano)	1308f	12/2/78	-7.7	-52.7	
	WP10	14.26.10.222	1161f	4/1/78	-7.4	-56.9	
		(Hagerman Municipal Well)	1307f	12/2/78	-7.8	-54.1	
	WP11	15.26.04.141	1309f	12/2/78	-7.7	-58.5	
		(Jake Johnson Farm)					
	WP12	15.26.13.121	2506	9/17/77	-9.4	-51*	4.1±0.8
		(Pollard Well)	2512	4/1/78	-9.0	-55*	1.9±0.6
				(pumping 978 gpm)			
	WP14	17.26.10.333	1958	8/28/75	-5.0		9.6±0.4
		(Gates RA 307)	2128	6/4/76	-6.3		4.2±0.3
		irrigation		(pumping 800 gpm)			
			2199	8/11/76	-6.7		9.7±1.0
				(pumping 500 gpm)			
			2598	3/25/77	-7.0		7.9±0.7
			2605	7/1/77	-6.1		7.1±0.5
			2607	9/17/77	-7.4		6.9±0.7
			2608	4/1/78	-6.7	-77*	4.9±0.6
		(2598-2608: flowmeter not indicating)					
			Mean of Gates		-6.5		
	WP14	17.26.10.433	1167f	4/1/78	-7.3	-42.6	
				(pumping 400 gpm)			
		(Sullivan	1379f	4/1/79	-7.9	-48.6	
		(Pennington) Farms)		(pumping 830 gpm)			
	WP15	17.26.14.211	2536	9/17/77	-7.5		3.8±0.8
		(Sharp RA 895)		(pumping 652 gpm)			
			2542	4/1/73	-7.6		2.7±0.8
				(pumping 455 gpm)			

Table A1

Roswell Groundwater Basin
Oxygen 18, Deuterium, and Tritium Analyses of Water Samples

Type of samples	Map #	Sample Location	Sample #	Date Collected	$\delta^{18}O$ $^{0}/_{00}$	δD $^{0}/_{00}$	Tritium (T.U.)
Miscellaneous Snow Samples		Sierra Blanca Ski Area					
		Near top of gondola (11,400 ft)	2612	2/3/79		-134*	26.7±1.1
		Top of Moonshine Gulch	2611	2/3/79	-17.0		28.9±1.3
		Ski area base . . .	1350f	2/3/79		-145*	
		Sierra Blanca Rd. 0.8 miles above Oak Grove Campground	2255	10/28/76	-12.6		29.8±0.9
		Oak Grove Campground .	2256	10/28/76	-12.0		30.3±1.0
		Sierra Blanca Rd., turnoff to Oak Grove Campground. . . .	2614	2/3/79	-16.8		32.5±1.4
		Sierra Blanca Rd., turnoff to Mon Jeau Lookout.	2615	2/3/79		-133*	32.4±0.9
		Intersection of NM 48 & Sierra Blanca Rd. .	2257	10/28/76	-14.5		11.8±1.1
		Bonito Lake	2558	1/16/79	-21.2	-146.1	34.1±1.4
		Swiss Chalet Inn @	2551	1/16/79	-13.8		24.4±1.0
		Alto, N.M. . . .	2616	2/2/79	-7.1		29.4±0.9
		Apache Summit . . .	2550	1/15/79	-22.0		25.8±1.3
		National Park Snow Play Area	2546	1/14/79	-21.8	-157.6	24.7±1.3
		Cloudcroft Ski Area base.	2547	1/14/79	-18.5		26.5±0.9
		St. James Campground .	2548	1/14/79	-15.4	-102.1	18.7±1.2
		16.16.08.121 (Bates Windmill)	2258	10/29/76	-13.0		23.8±1.2
		15.18.18.000 (Flying H Ranch)	2268	10/29/76	-13.0		21.9±1.3
Precipitation		Roswell Weather Bureau (3669′ a.m.s.l.)	2628	3/76	-9.6		55.3±2.0
			2704	4/76	-10.0	-71*	32.4±1.4
			2629	6/76	-4.3		62.2±1.6
			2242	7/76 & 8/76	-4.8	-35.0	
			2454	9/76 & 10/76	-6.2	-50*	36.5±1.7
			762f	2/77	-3.8		
			2638	3/77 & 4/77	-6.4	-44.1	76.7±1.6
			2639	5/77	-5.7		74.1±2.4
			CRD4	6/77	-0.4		
			2557	7/77	-0.8	-5*	75.3±2.5
			2637	8/77	-6.6		49.8±1.4
			2523	8/12/77	-6.0		28.7±0.9
			CRD5	9/77	-2.7		
			2571	10/77	-6.4	-28*	51.8±1.7

Table A1

Roswell Groundwater Basin
Oxygen 18, Deuterium, and Tritium Analyses of Water Samples

Type of samples	Map #	Sample Location	Sample #	Date Collected	$\delta^{18}O$ ‰	δD ‰	Tritium (T.U.)
Precipitation (continued)			2409	11/77 - 1/78	-9.7		29.0±1.4
			1114f	2/78	-13.8		
			(in 2560)				
			2540	3/78	-18.6	-149*	149.3±2.2
			1229	5/78	-8.1		
			(in 2560)				91.7±2.6
			1230	6/78	-4.8		
			CR110	7/78	-0.5		
			CR108	8/78	-3.8		
			CR109	9/78	-7.7	-63.8	

TABLE A3. Climatological Data* and $\delta^{18}O$ in Precipitation at Elk

	1976				1977				1978			
	Precip. (inches)	Temperature (°C)		$\delta^{18}O$ ($^{o}/oo$)	Precip. (inches)	Temperature (°C)		$\delta^{18}O$ ($^{o}/oo$)	Precip. (inches)	Temperature (°C)		$\delta^{18}O$ ($^{o}/oo$)
January	0.29	2.56	NS***	-12.5	0.76	1.89	0.37	-18.1	0.84	2.22	1.11	-15.5
February	0.64	7.50	NS	-10.0	0.29	5.33	0.69	-7.6	0.36	2.50	1.94	-13.8
March	0.18	7.22	NS	-10.1	0.15	5.67	-0.28	-10.5	0.50	8.00	3.33	-18.6
April	0.58	11.61	10.97	-8.5	1.49	10.78	6.53	-9.4	0.47	11.94	NS	-7.7
May	2.01	14.17	11.78	-11.1	1.12	15.00	15.00	-3.7	1.88	15.78	15.39	-8.1
June	1.22	19.28	17.64	-4.7	1.38	20.56	14.03	-3.6	2.06	21.22	19.44	-4.8
July	3.50	19.22	18.64	-7.7	1.57	21.22	21.00	-0.5	1.56	21.89	20.35	-0.5
August	1.01	19.83	19.81	-2.0	2.33	21.72	21.15	-0.9	4.65	20.44	20.44	-3.8
September	2.14	15.39	13.47	-7.5	1.43	19.33	17.85	-6.7	7.06	16.22	12.43	-7.7
October	1.37	9.06	-1.39	-11.8	0.65	13.28	15.69	-7.7	2.45	12.89	NS	-7.2
November	1.03	NO	NO****	-11.5	0.62	7.44	9.72	-10.1	2.54	8.22	NS	-9.6
December	0.00	-1.06	--	--	0.09	6.61	5.00	-7.9	0.88	2.50	NS	-12.5

Weighted Mean $\delta^{18}O = -7.1 \pm 0.3\ ^{o}/oo$

* From NOAA: Local Climatological Data

** Left column: monthly average. Right column: average for days on which precipitation sample available

*** No sample. $\delta^{18}O$ was calculated from the relation: $\delta^{18}O = 0.52t - 13.83$ (Figure 6), and left-column temperature

**** No data (point not used).